Experimental evidences of Luttinger liquid behavior in the crossed multi-wall carbon nanotubes

Jinhee Kim[1], Kicheon Kang[2], Jeong-O Lee[2], Kyung-Hwa Yoo[1], Jae-Ryoung Kim[2], Jong Wan Park[1], Hye Mi So[2], and Ju-Jin Kim[2]

[1] *Electricity Group, Korea Research Institute of Standards and Science, Yusong-gu P.O.Box 102, Taejon, 305-600, Korea*

[2] *Department of Physics, Chonbuk National University, Chonju 561-756, Korea*

(February 1, 2008)

Luttinger liquid behavior was observed in a crossed junction formed with two metallic multi-wall carbon nanotubes whose differential conductance vanished with the power of bias voltage and temperature. With applying constant voltage or current to one of the two carbon nanotubes in a crossed geometry, the electrical transport properties of the other carbon nanotube were affected significantly, implying there exists strong correlation between the carbon nanotubes. Such characteristic features are in good agreement with the theoretical predictions for the crossed two Luttinger liquids.

PACS numbers: 71.10.Pm, 73.61.-r, 73.40.Gk

The non-Fermi liquid behavior of low dimensional systems is one of the most challenging subjects in recent theoretical and experimental studies [1–4]. In one dimension, electron-electron interaction is known to invalidate the Fermi liquid description of metal and gives a new physical state, Luttinger liquid (LL), which is characterized by the spin-charge separation and the absence of single-particle excitation at low energy, etc. Until now, many experiments, mostly with the compound semiconductors [1], have been performed regarding the LL behavior of low dimensional conductor. The experimental results seem to support non-Fermi liquid behavior of one-dimensional conductor but conclusive evidence of the LL behavior is still to come.

Carbon nanotube (CNT) [5] is known to be an ideal system to test the LL behavior of one-dimensional system [2–4]. Previous experiment on single-wall CNT by Bockrath *et al.* [2] has shown that the tunneling density of states vanishes both with temperature and bias voltage in the power-law functional form. However, the electrical transport properties of single-wall CNT in their measurements were dominated by the Coulomb blockade effect at low bias region, which might mask the LL behavior. Recently, Komnik and Egger [3] have proposed an elegant way to verify the LL behavior of one-dimensional conductor. They have shown that if two LLs are contacted in a point-like manner, the electrical transport through one LL is perturbed significantly by the bias voltage applied to the other LL. A previous experiment on the crossed single-wall CNT [6] did not show the LL behavior theoretically predicted [3], probably because of the large Coulomb blockade effect in each CNT. To test these theoretical predictions and detect possible deviation from the Fermi liquid theory, we have fabricated a cross junction formed with two metallic multi-wall CNTs. With single-wall CNTs, it is not easy to form a cross junction with enough electrostatic interaction between two CNTs which is essential to observe LL behavior in the crossed geometry [3]. Due to the relative easiness of forming low-ohmic cross junction and weak Coulomb blockade effect compared to the single-wall counterpart, the multi-wall CNT has great advantages to test the LL behavior of CNT. Further, it is important to note that multi-wall CNT, as well as single-wall CNT, is predicted to show LL behavior in the limit of small number of conducting channels [4].

In this Letter, we report experimental evidences of LL behavior of multi-wall CNTs in the crossed geometry. Each CNT in the sample showed vanishing tunneling density of states with bias voltage in the power-law functional form, which is one of the signatures of LL behavior. The differential conductance curves at different temperatures are collapsed well into a single scaling curve. We have also measured the differential conductance of one CNT with applying constant voltage to the other CNT and observed that the differential conductance of one CNT is strongly influenced by the voltage applied to the other CNT [3]. Furthermore, it is found that the off-diagonal differential resistance curve in the cross junction shows highly non-linear behavior along with negative differential resistance, which is another indication of the existence of strong correlation between two CNTs. All the experimental results support the LL behavior of multi-wall CNTs.

The multi-wall CNT used in this measurement was synthesized by arc discharge method. To select single CNT we have dispersed ultrasonically the CNT in chloroform for about half an hour and then dropped a droplet of the dispersed solution on the Si substrate with 500 nm-thick thermally-grown SiO_2 layer. The multi-wall CNTs in the crossed form were searched by scanning electron microscope (SEM). The patterns for electrical leads were generated using e-beam lithography technique onto the selected CNTs and then 20 nm of Ti and 50 nm of Au were deposited successively on the contact area by thermal evaporation. Shown in Fig. 1 is the SEM photograph of the crossed CNTs with the electric leads labeled. The atomic force microscope study has shown that the diam-

eter of the CNT was in the range of 25 - 30 nm. In order to form low-ohmic contacts between the CNT and the Ti/Au electrodes, we have performed rapid thermal annealing at 800 C for 30 sec [8]. The contact resistances are in the range of 5 kΩ - 18 kΩ at room temperature and become 10 kΩ - 60 kΩ at 4.2 K. The cross junction has junction resistance of 5.4 kΩ at room temperature and 16.8 kΩ at 4.2 K. The four-terminal resistance of each CNT increases monotonically with lowering temperature and depends sensitively on the bias current level, implying non-ohmic current-voltage characteristics of the CNT [8].

We have measured the current-voltage (I-V) characteristics both in two- and four-terminal measurement configurations. The differential conductance-voltage curve (dI/dV-V) was then obtained by numerically differentiating the I-V characteristics. Insets of Fig. 2 display the four-terminal dI/dV-V curves of each CNT as a function of temperature. Subtracting the contact resistance, both two- and four-terminal measurements give nearly identical dI/dV-V curves. As shown in the insets of Fig. 2, the differential conductance, which is proportional to the density of states near the Fermi level, vanishes at low bias as the temperature is lowered. We have found that the density of states vanishes with the bias voltage in the power-law functional form, $G \sim V^{\alpha}$, with $\alpha = 0.3$ for the nanotube horizontally placed in Fig. 1 (from now on we call it CNT-1) and $\alpha = 0.9$ for the nanotube vertically placed (CNT-2). By using the relation between the exponent and the Luttinger parameter for an end-contacted LL [2],

$$\alpha = \left(\bar{g}^{-1} - 1\right)/4 \qquad (1)$$

where $\bar{g}$ is the effective Luttinger parameter for crossed LL [3] given by $\bar{g} = 2g$, we get $g = 0.23$ for CNT-1 and $g = 0.11$ for CNT-2.

For a LL, the temperature dependence of low-bias conductance is also expected to show the power-law functional form, $G(V \approx 0) \sim T^{\alpha}$. One way to exhibit this behavior is to plot the scaled differential conductance, $T^{-\alpha} dI/dV$, as a function of the scaled voltage, $eV/k_B T$ [2]. As shown in the main panels of Fig. 2, the scaled differential conductance curves for different temperatures fall well into a single scaling curve, except for high bias voltage where the differential conductance becomes saturated. Two CNTs showed similar scaling behavior but with different exponent α. Such scaling behavior of the differential conductance curves is an indication of probable LL behavior of the two CNTs in the sample. The exponent α depends on the sample geometry.

The LL behavior of CNTs was further verified by the two-terminal differential conductance curves of CNT in a crossed geometry proposed by Komnik and Egger [3]. We have measured the differential conductance of the CNT-1, dI_{34}/dV_{34}, with applying bias voltage V_{56} to the CNT-2. Fig. 3 (a) shows the measured differential conductance curves with varying bias voltage V_{56} from -24 mV to +21.6 mV with the increment of 2.4 mV. For V_{56} close to zero, typical differential conductance curves with vanishing dI/dV in a power of V were shown. With increasing the magnitude of V_{56}, the zero-bias conductance increases rapidly and for $|V_{56}| > 12$mV, the zero-bias differential conductance dI_{34}/dV_{34} ($V_{34} = 0$) switches from a dip to a peak. In addition the differential conductance curve begins to exhibit two separated dips at finite voltages. This characteristic feature agrees very well with the theoretical prediction [3] and is one of experimental evidences of the strong correlation between the two CNTs. Such a strong dependence of the differential conductance dI_{34}/dV_{34} on the bias V_{56} may not be easily understood within the framework of the non-interacting electron picture [7]. The dip separation increases monotonically with $|V_{56}|$. Following Komnik and Egger [3], the conductance dip should appear at $|V_{56}| = |V_{34}|$ for two identical LLs with $g = 1/4$, a special point where an exact I-V curve was calculated. We have plotted the dip position V_{34} as a function of V_{56} in Fig. 3 (b). As expected, the peak position V_{34} increases or decreases linearly with V_{56}. Best fit gives the magnitude of the linear slopes close to 0.21, about 5 times smaller than that of the predicted ones for the two identical LLs. In our case, two CNTs have different Luttinger parameters, $g = 0.23$ for CNT-1 and $g = 0.11$ for CNT-2, respectively, which might be the origin of the discrepancy.

We have also measured the current-voltage characteristics with applying current to one CNT and measuring voltage drop on the other CNT in the crossed geometry. Fig. 4 shows the voltage-current characteristics, V_{34}-I_{56}, and the off-diagonal differential resistance (ODR)-current curve, dV_{56}/dI_{34}-I_{34}, measured at $T = 50$ mK. A noticeable feature is the highly-non-linear behavior of the ODR together with the existence of the negative differential resistance (NDR) at low bias region. This can be interpreted as another indication of the existence of strong correlation between two CNTs which are considered to be LLs. The interchange of the voltage and the current leads gives almost identical voltage-current characteristics. The NDR and asymmetry in the ODR can be understood in a simple argument. The ODR can be written by

$$R_{ab} = \frac{-G_{ab}}{G_{aa}^2 - G_{ab}^2} \ , \qquad (2)$$

where G_{aa} and G_{ab} are the diagonal and the off-diagonal conductances given in Ref. [3]. Here the indices a, b denote the current and the voltage probes in a given measurement configuration, respectively. It can be shown that for $g < 1/2$, G_{ab} is non-zero and bound by $-G_0/2 < G_{ab} < G_0/2$, where G_0 is the unit conductance of the system (in our case $G_0 = 4e^2/h$), and can be asymmetric

under the bias reversal. Then R_{ab} can be negative and also be asymmetric under the bias reversal. These features are well shown in Fig. 4.

In summary, we have investigated electrical transport properties of the crossed multi-wall CNTs. Each nanotube showed the tunneling density of states vanishing with the power of bias and temperature at low energy limit, which is an evidence of the LL behavior. The differential conductance curves of one CNT were disturbed significantly by applying bias voltage to the other one in a crossed geometry. This characteristic feature is an indication that strong correlation exists between the two crossed CNTs. With increasing bias voltage, two dips appear in the differential conductance curves and the dip separation increases linearly with the bias voltage, which is consistent with the theoretical prediction for two crossed LLs. Furthermore, the off-diagonal differential resistance exhibited highly non-linear behavior with negative differential resistance. We conclude that all these experimental results support the LL behavior of multi-wall CNTs.

We thank G. Cuniberti, H.-W. Lee, and H. S. Sim for helpful discussions and comments. This work was supported by the MOST through Nano Structure Project, Korea Research Foundation Grant (KRF-99-015-DP0128), BK21 project, and also by KRISS (Project No. 00-0502-100).

[1] S. Tarucha, T. Honda, and T. Saku, Solid State Comm. **94**, 413 (1995); F. P. Miliken, C. P. Umbach, and R. A. Webb, *ibid.* **97**, 309 (1995); A. M. Chang, L. N. Pfeiffer, and K. W. West, Phys. Rev. Lett. **77**, 2538 (1996); M. Grayson *et al.*, *ibid.* **80**, 1062 (1998); A. Yacoby *et al.*, *ibid.* **77**, 4612 (1996); O. M. Auslaender *et al.*, *ibid.* **84**, 1764 (2000); Q. Si, *ibid.* **81**, 3191 (1998); C. Winkelholz, R. Fazio, F. W. J. Hekking, and G. Schön, *ibid.* **77**, 3200(1996).

[2] M. Bockrath *et al.*, Nature **397**, 598 (1999).

[3] A. Komnik and R. Egger, Phys. Rev. Lett. **80**, 2881 (1998).

[4] R. Egger, Phys. Rev. Lett. **83**, 5547 (1999).

[5] C. Dekker, Physics Today **52**, 22(1999); J. W. G. Wildöer *et al.*, Nature **391**, 59 (1998); T. W. Odom, J.-L. Huang, P. Kim, and C. M. Lieber, *ibid.*, 62 (1998) ; L. C. Venema, *et al.*, Science **283**, 52 (1999); S. Frank, P. Poncharal, Z. L. Wang, W. A. de Heer, *ibid.* **280**, 1744 (1998); A. Bachtold, *et al.*, Nature **397**, 673 (1999); L. Langer *et al.*, Phys. Rev. Lett. **76**, 479 (1996); Z. Yao *et al.*, Nature **402**, 273 (1999); Z. Yao *et al.*. Phys. Rev. Lett. **84**, 2941 (2000); C. Schönenberger, *et al.*, unpublished (cond-mat/9905114).

[6] M. S. Fuhrer *et al.*, Science **288**, 494 (2000).

[7] M. Büttiker, Phys. Rev. Lett. **57**, 1761 (1986).

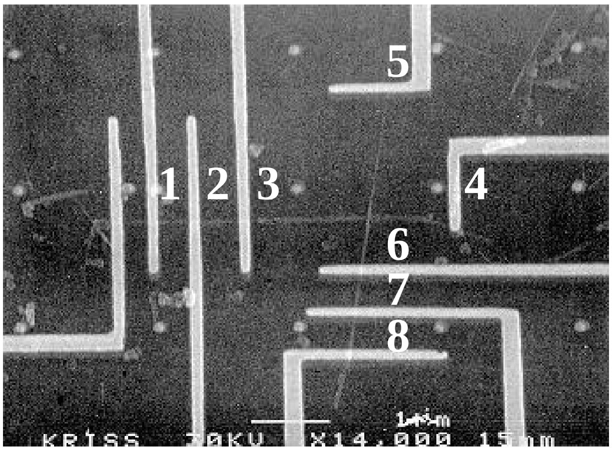
[8] J.-O. Lee *et al.*, to appear in Phys. Rev. B (2000).

FIG. 1. The scanning electron microscope image of the sample studied. For convenience, the electrical leads are numbered.

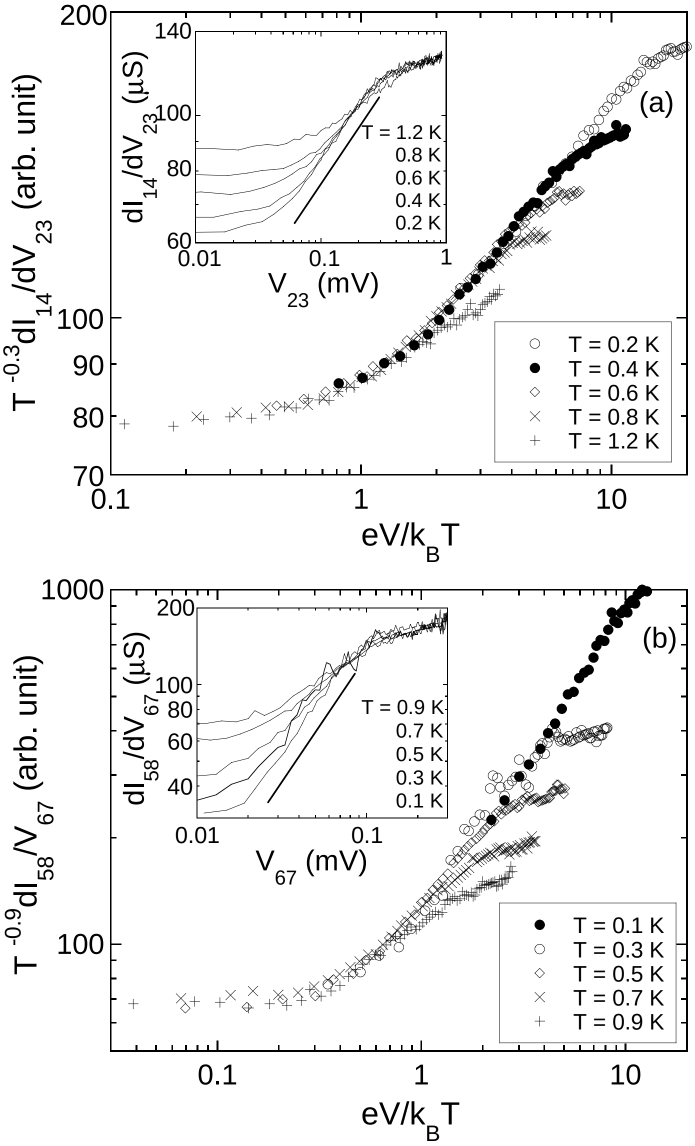
FIG. 2. The scaled conductance $T^{-\alpha} dI/dV$ as a function of the scaled voltage eV/k_BT with (a) $\alpha = 0.3$ for the CNT horizontally placed in Fig. 1 (CNT-1) and (b) $\alpha = 0.9$ for the CNT vertically placed (CNT-2). Insets show the log-log plots of the four-terminal differential conductance-voltage curves for CNT-1 and CNT-2 at temperatures listed. The solid lines are guides to show the power-law dependence of the tunneling density of states.

FIG. 3. (a) The two-terminal differential conductance-voltage (dI_{34}/dV_{34} - V_{34}) curves of the CNT-1 with varying bias voltage to the CNT-2, V_{56}, from -24 mV to +21.6 mV with the increment of 2.4 mV at temperature $T = 50$ mK. For clarity, each curve was displaced vertically. (b) The dip position, V_{34}, in the differential conductance-voltage curves of the CNT-1 as a function of the bias voltage to the CNT-2, V_{56}. The solid lines are linear fits to the data.

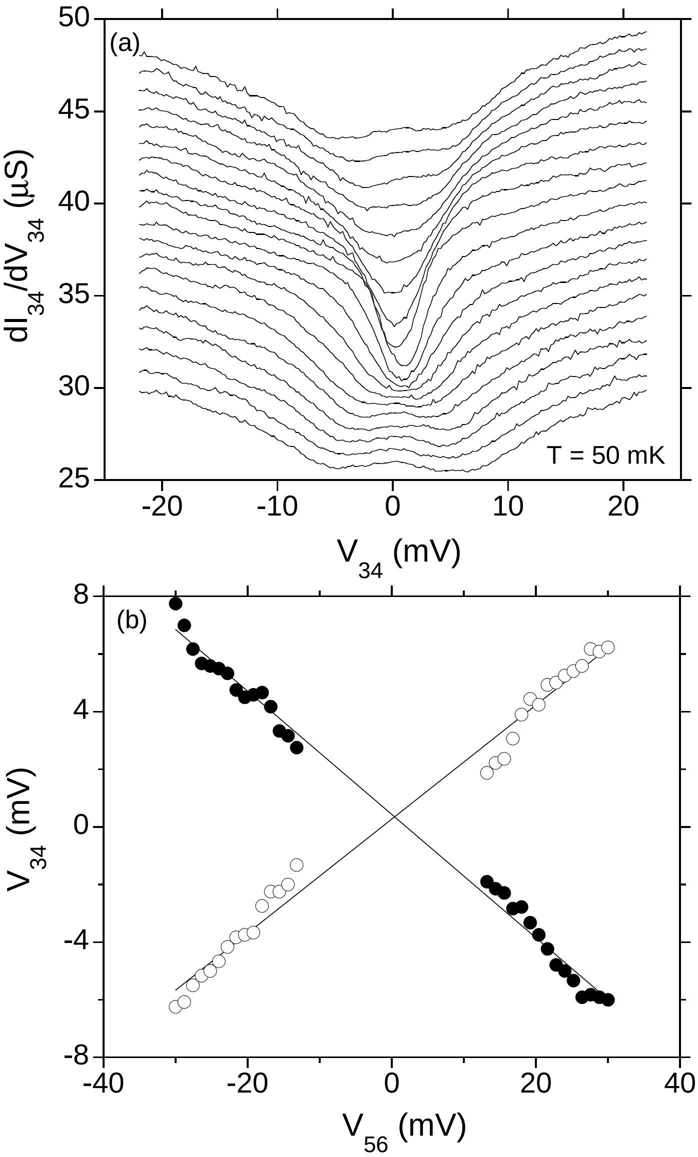
FIG. 4. The off-diagonal voltage-current and differential resistance-current curves at temperature $T = 50$ mK. We have applied bias current to the leads 3 and 4 and measured the voltage drops between the leads 5 and 6.

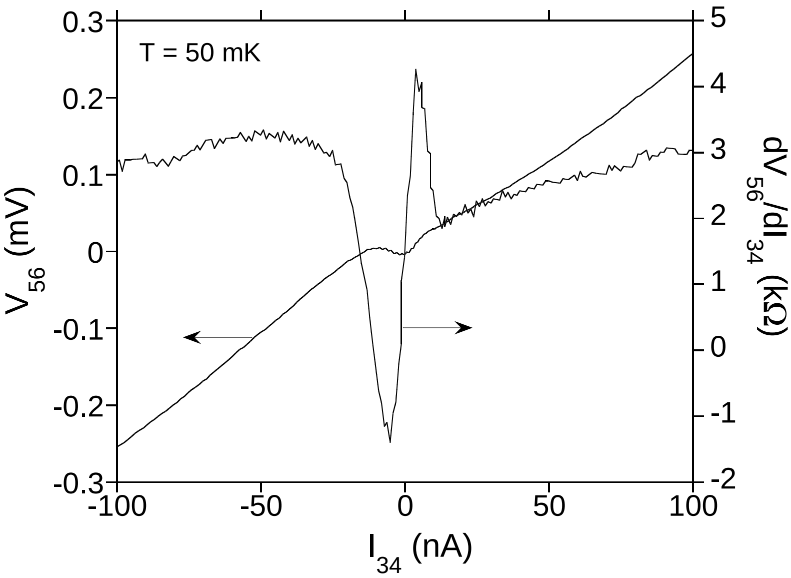


5
1
2
3
4
6
7
8
KRISS 30KV X14,000 15mm



(a)
$T^{-0.3} dI_{14}/dV_{23}$ (arb. unit)
eV/k_BT
T = 0.2 K
T = 0.4 K
T = 0.6 K
T = 0.8 K
T = 1.2 K
dI_{14}/dV_{23} (μS)
V_{23} (mV)
T = 1.2 K
0.8 K
0.6 K
0.4 K
0.2 K
(b)
$T^{-0.9} dI_{58}/V_{67}$ (arb. unit)
eV/k_BT
T = 0.1 K
T = 0.3 K
T = 0.5 K
T = 0.7 K
T = 0.9 K
dI_{58}/dV_{67} (μS)
V_{67} (mV)
T = 0.9 K
0.7 K
0.5 K
0.3 K
0.1 K


(a)
T = 50 mK
dI_{34}/dV_{34} (μS)
V_{34} (mV)
(b)
V_{34} (mV)
V_{56} (mV)


T = 50 mK
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
V_{56} (mV)
5
4
3
2
1
0
-1
-2
dV_{56}/dI_{34} (kΩ)
-100
-50
0
50
100
I_{34} (nA)